Motion, Mass, and Density

Physical Quantities and Measurement Techniques

1. Finding Length and Volume

Using a Ruler to Find Length

- **Instrument:** A ruler (or metre rule for longer lengths).
- **How to Use:**
    1. **Align Correctly:** Place the object so that one end is flush with the '0' mark of the ruler.
    2. **Eye Level:** Place your eye directly above the other end of the object to avoid **parallax error** (a viewing error that gives an incorrect reading).
    3. **Read the Scale:** Note the value on the ruler where the object ends.
- **Example:** To measure the length of a book, place the book's edge at the 0 cm mark and read the scale at the other edge.

Using a Measuring Cylinder to Find Volume

- **Instrument:** A measuring cylinder (used for liquids and irregular solids).
- **How to Use (for a Liquid):**
    1. **Place on a Flat Surface:** This ensures the cylinder is vertical.
    2. **Read the Meniscus:** The surface of a liquid is curved (a meniscus). Always read the volume at the **bottom of the meniscus** at eye level to avoid parallax error. The volume is measured in millilitres (ml) or cubic centimetres (cm^3), where 1 ml = 1 cm^3.
- **How to Use (for an Irregular Solid, e.g., a rock):**
    1. **Partially Fill** the cylinder with water and note the volume (e.g., V_1 = 50 ml).
    2. **Carefully Lower** the object into the water so it is fully submerged.
    3. **Note the New Volume** (e.g., V_2 = 65 ml).
    4. **Calculate the Volume:** Volume of object = $V_2 - V_1$ = 65 ml - 50 ml = **15 cm^3** (since 1 ml = 1 cm^3).

2. Measuring Time Intervals

Using Clocks and Digital Timers

- **Instrument:** Clocks (analogue or digital) for longer periods; stopwatches (digital or analogue) for shorter, more precise intervals.
- **How to Use:**
    - **For a Clock:** Note the start and end times and subtract to find the duration. (e.g., Start: 10:05:00, End: 10:07:30, Duration: 2 minutes 30 seconds).
    - **For a Digital Stopwatch:**
        1. **Start:** Press the start button at the beginning of the event.
        2. **Stop:** Press the stop button at the end of the event. The display shows the time interval that has passed.
        3. **Reset:** Press the reset button to return the display to zero.
- **Measuring a Variety of Intervals:**
    - **Short Interval (e.g., a car rolling down a ramp):** Use a digital stopwatch for precision.
    - **Long Interval (e.g., time to boil water):** A clock or a timer with a minute hand is sufficient.
    - **Reaction Time:** Human error in starting/stopping a stopwatch is called **reaction time error**. For very short events, this can be significant.

3. Finding Averages by Measuring Multiples

This technique improves accuracy for measuring very small quantities where a single measurement would be unreliable.

Average Value for a Small Distance

- **Principle:** Instead of measuring one thin object (like a sheet of paper), measure the total thickness of a large stack.
- **Method:**
    1. Measure the total thickness of a stack of, for example, 100 sheets of paper using a ruler.
    2. Divide the total thickness by the number of sheets.
- **Formula:** Average Thickness of one sheet = Total Thickness ÷ Number of Sheets
- **Example:** 100 sheets have a total thickness of 1.2 cm.
    - Average thickness per sheet = 1.2 cm ÷ 100 = **0.012 cm** (or 0.12 mm).

Average Value for a Short Time Interval (Period of a Pendulum)

- **Principle:** The time for one complete swing (from left to right and back to left) is the **period**. It is difficult to measure one swing accurately due to reaction time. Measuring the time for multiple swings reduces this error.
- **Method:**
  1. **Time Multiple Swings:** Measure the total time for, for example, 20 complete oscillations.
  2. **Calculate the Average:** Divide the total time by the number of oscillations.
- **Formula:** Period (T) = Total Time for 'n' oscillations ÷ n
- **Example:** Time for 20 oscillations = 28.4 seconds.
  - Period, T = 28.4 s ÷ 20 = **1.42 seconds**.

Why this works: The reaction time error (e.g., ±0.2 s) is spread over all 20 oscillations, making the calculated period much more accurate than if you timed just one swing.

Scalars and Vectors

Physical quantities can be classified as either **scalar** or **vector** quantities.

Quantity Type	***Definition***	***Key Characteristics***	***Examples***
Scalar	A quantity that has **magnitude** (size) only.	Does not have a direction.	Distance, Speed, Mass, Time, Energy, Density, Temperature
Vector	A quantity that has both **magnitude** and **direction**.	Direction is essential for a complete description.	Displacement, **Velocity**, **Acceleration**, **Force** (Weight), Momentum

Calculating with Vectors (Vector Addition)

Vector addition is required when two or more forces or velocities act on an object.

1. **Vectors in the same direction:** Add the magnitudes.
   - *Example:* A force of 5N east and a force of 3N east result in a resultant force of 8N east.
2. **Vectors in opposite directions:** Subtract the smaller magnitude from the larger one. The resultant vector is in the direction of the larger vector.

- *Example:* A force of 5N east and a force of 3N west result in a resultant force of 2N east.

3 **Vectors at right angles:**

—By calculation(Pythagoras & trigonometry)

-Step 1:sketch

Draw the two vectors acting at a right angle head to tail. Then, complete the rectangle or triangle by drawing the resultant vector from the tail of the first to the head of the second.

-Step 2: Find the Magnitude (Size)

Because the vectors are at right angles (90°), they form two sides of a right-angled triangle. The resultant is the hypotenuse.

- **Formula:** $a^2 + b^2 = c^2$
- Where:
  - a and b are the magnitudes of the two vectors.
  - c is the magnitude of the resultant vector.

-Step 3: Find the Direction (Angle)

Use trigonometry on your sketch to find the angle (θ) the resultant makes with a reference direction.

- **Formula:** $\tan(\theta) = \text{Opposite} / \text{Adjacent}$
- You can then use the inverse tan function ($\tan^{-1}$) on your calculator to find the angle θ.

—By Graphical Method (Scale Drawing)

This method is visual but less precise. Its accuracy depends on the quality of your drawing and measuring.

-Step 1: Choose a Scale

Select a scale that fits your paper (e.g., `1 cm = 1 N` or `1 cm = 50 km/h`).

-Step 2: Draw the Vectors to Scale

- Draw the first vector as an arrow of the correct length and direction.
- From the tip (head) of the first vector, draw the second vector to scale and at the correct right angle.

-Step 3: Complete the Triangle

Draw the resultant vector as an arrow from the *tail* of the first vector to the *head* of the second vector.

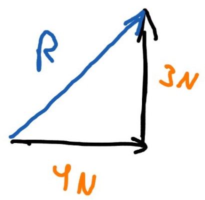
Step 4: Measure the Resultant

- **Magnitude:** Measure the length of the resultant arrow with a ruler and convert back to real units using your scale.
- **Direction:** Measure the angle between the first vector and the resultant vector using a protractor.

Worked Example: Two Forces

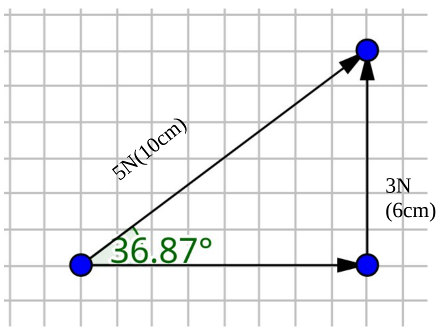
A force of 3 N acts north, and a force of 4 N acts east. Find the resultant force.

1)Calculation



1. **Magnitude:**
   - Let $a = 3$ N (North), $b = 4$ N (East).
   - Resultant magnitude, $R = \sqrt{(3^2 + 4^2)}$
   - $R = \sqrt{(9 + 16)} = \sqrt{25}$
   - $\mathbf{R = 5\ N}$
2. **Direction:**
   - From the sketch, the angle (θ) from horizontal by:
   - $\tan(\theta) = \text{Opposite} / \text{Adjacent} =$ (North 3 N) / (East 4 N)
   - $\tan(\theta) = 3/4 = 0.75$
   - $\theta = \tan^{-1}(0.75)$
   - $\boldsymbol{\theta \approx 36.9°}$

2)Scale drawing



Let each small square = 1 cm

Scale is 1N : 2cm

4N (8cm)

Final Answer: The resultant force is **5 N at an angle of 36.9° from horizontal**.

2. Motion

Speed and Velocity

Quantity	**Definition**	**Formula**	**Unit**	**Type**
Speed *(v)*	Distance travelled per unit time.	$$v = \frac{\text{distance}}{\text{time}}$$	m/s	Scalar
Velocity *(v)*	Displacement per unit time, or speed in a given direction.	$$v = \frac{\text{displacement}}{\text{time}}$$	m/s	Vector

Average Speed is calculated using the total distance traveled and the total time taken:

Average speed = $\frac{Total\ distance\ traveled}{Time\ taken}$

Worked Example: Calculating Distance

A plane flies at an average speed of 250m/s for 2 hours Calculate the distance traveled.

Step 1: Convert time to standard units (seconds). 2 hours × 60 × 60 = 2700s

Step 2: Use the speed formula, rearranged for distance. Distance = Speed × Time

Distance = 25m/s × 7200s = 1,800,000 m

Answer: The distance traveled is 1,800,000m (or 1800km).

Acceleration

Acceleration (a) is the rate of change of velocity. It is a **vector** quantity.

Acceleration (a) = $\frac{Change\ is\ velocity}{Time\ taken} = \frac{v - u}{t}$

Where:

- a = acceleration (m/s^2)
- v = final velocity (m/s)
- u = initial velocity (m/s)
- t = time taken (s)
- **Positive acceleration** means the object is speeding up.
- **Negative acceleration** (or **deceleration**) means the object is slowing down.

Worked Example: Calculating Acceleration

A car accelerates from rest (0 m/s) to a velocity of 20 m/s in 5 s. Calculate its acceleration.

Step 1: List the known values.

- Initial velocity (u) = 0 m/s
- Final velocity (v) = 20 m/s
- Time (t) = 5 s

Step 2: Use the acceleration formula.

$$a = \frac{v - u}{t}$$

$$a = \frac{20\ m/s - 0\ m/s}{5\ s}$$

$$a = \frac{20}{5} = 4\ m/s^2$$

Answer: The car's acceleration is 4 m/s^2.

Graphical Analysis of Motion

Distance-Time Graphs

Graph Feature	**Meaning**
Gradient (Slope)	**Speed**
Horizontal line	Stationary (Speed = 0)
Straight line with positive gradient	Constant speed
Curved line (increasing gradient)	Accelerating (Speed is increasing)
Curved line (decreasing gradient)	Decelerating (Speed is decreasing)

Speed-Time Graphs

Graph Feature	**Meaning**
Gradient (Slope)	**Acceleration**
Area under the graph	**Distance Travelled**
Horizontal line	Constant speed (Acceleration = 0)
Straight line with positive gradient	Constant acceleration
Straight line with negative gradient	Constant deceleration

Worked Example: Calculating Distance from a Speed-Time Graph

A speed-time graph shows a car speeding up at a constant acceleration from 0 ms^{-1} to 10 ms^{-1} in 5 s. It then travels at constant speed for 5 seconds before decelerating uniformly to rest in another 5 seconds. Calculate the distance traveled.

Step 1: Identify the shape. The area under the graph of a triangle from (0,0) to (5,10), a rectangle from (5,10) to (10,10), and a triangle from (10,10) to (15,0)

Step 2: Calculate the area (distance).
Area 1 (acceleration): 0.5 × 5s × 10m/s = 25m
Area 2 (constant speed): 5s × 10m/s = 50m
Area 3 (deceleration): 0.5 × 5s × 10m/s =25m
Total distance = 25m + 50m + 25m = 100m
Answer: The distance traveled is 10 m.

Freefall and Terminal Velocity

- **Freefall** is the motion of an object under the influence of gravity only, with no air resistance. In a vacuum, all objects fall with the same constant acceleration ($g \approx 9.8$ m/s^2).
- **Air Resistance** (or drag) is a force that opposes motion through the air. It increases with speed.

Terminal Velocity (Extended Content)

When an object falls through the air, it eventually reaches a constant maximum velocity called terminal velocity.

1. **Start:** The object accelerates due to **Weight** (force of gravity). Air resistance is zero.
2. **Acceleration:** As speed increases, **Air Resistance** increases. The resultant force (Weight - Air Resistance) decreases, so acceleration decreases.
3. **Terminal Velocity:** Air Resistance becomes equal to the Weight. The resultant force is zero, so the object moves at a constant velocity (zero acceleration).

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3. Mass, Weight, and Density

Mass and Weight

Quantity	Definition	Unit	Type	Location Dependence
Mass (m)	A measure of the quantity of matter in an object.	kg	Scalar	**Constant** everywhere in the universe.
Weight (W)	The force of gravity acting on an object's mass.	N	Vector	**Varies** depending on the gravitational field strength (g).

Gravitational Field Strength

Gravitational Field Strength (g) is the force per unit mass acting on an object in a gravitational field.

$$\mathbf{W = m \times g}$$

$$\mathbf{g = W / m}$$

Where:

- **W** = Weight (N)
- **m** = Mass (kg)
- **g** = Gravitational Field Strength (N/kg)

On Earth, **g ≈ 9.8 N/kg**.

- **Note:** Gravitational field strength (g) is numerically equal to the acceleration of free fall (m/s^2).

Worked Example: Calculating Weight

An astronaut has a mass of 80 kg. Calculate their weight on Earth (g = 9.8 N/kg) and on the Moon (g = 1.6 N/kg).

Step 1: Calculate weight on Earth.

$W_{Earth} = m \times g_{Earth}$

W_{Earth} = 80 kg × 9.8 N/kg = 784 N

Step 2: Calculate weight on the Moon.

$W_{Moon} = m \times g_{Moon}$

W_{Moon} = 80 kg × 1.6 N/kg = 128 N

Answer: The astronaut's weight is **784 N** on Earth and **128 N** on the Moon. Their mass remains **80 kg** in both locations.

Density

Density (ρ) is defined as the mass per unit volume of a substance.

Density = Mass / Volume

$\rho = m / V$

Where:

- **ρ** = density (kg/m^3 or g/cm^3)
- **m** = mass (kg or g)
- **V** = volume (m^3 or cm^3)
- **High density** materials have a large mass packed into a small volume.
- **Low density** materials have a small mass spread over a large volume.

Determining Density

Liquids: Measure mass using a balance and volume using a measuring cylinder.
Regularly shaped solids: Measure mass using a balance and dimensions to calculate volume (e.g., length x width x height for a cuboid).
Irregularly shaped solids (sinking in liquid): Measure mass using a balance. Determine volume by the displacement method: immerse the solid in a measuring cylinder containing water and record the change in volume.

Worked Example: Calculating Density
A paving slab has a mass of 73 kg and dimensions 0.04 m × 0.5 m × 0.85 m. Calculate the density of the material.
Step 1: Calculate the volume (V).
$V = 0.04\ m \times 0.5\ m \times 0.85\ m = 0.017\ m^3$
Step 2: Use the density formula.
$\rho = m / V$
$\rho = 73\ kg / 0.017\ m^3 \approx 4294.1\ kg/m^3$
Step 3: Round to an appropriate number of significant figures (e.g., 2 s.f.).
$\rho \approx 4300\ kg/m^3$
Answer: The density of the paving slab material is approximately **$4300\ kg/m^3$**.

Floating and Sinking (Extended Content)

Whether an object floats or sinks in a liquid depends on its **density** compared to the liquid's density.

- An object will **float** if its density is **less than** the density of the liquid.
- An object will **sink** if its density is **greater than** the density of the liquid.
- An object will be **suspended** if its density is **equal to** the density of the liquid.

This principle is related to the **upthrust** (or buoyant force) exerted by the fluid, which is equal to the weight of the fluid displaced by the object (Archimedes' Principle).